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THICK PLATE MODEL FOR WARPING STRESSES IN CONCRETE PAVEMENTS

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Abstracts: *This paper develops a solution of warping stresses in concrete pavement slabs resting on the Pasternak foundation. The solution is derived using the Reissner thick plate theory. Warping stresses in a rectangular slab with four free edges is obtained by superposing the solutions of two finite slabs each of which has two guided support edges and two free edges, Finally, the proposed thick plate solution is compared with a thin plate solution to analyse limitation of the thin plate model.*

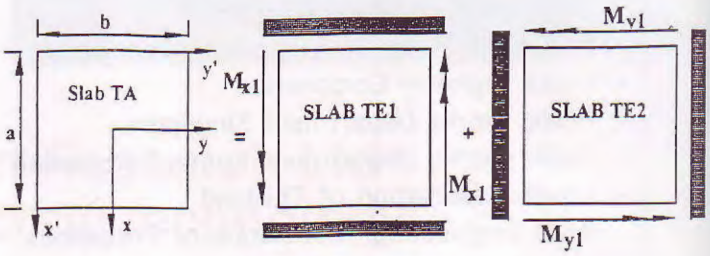
Introduction

It has been realised since early days that thermal warping stresses in concrete pavements are one of reasons that causes cracking in concrete pavements. Westergaard (1926) first developed an analytical model for the analysis of thermal warping stresses in concrete pavement slab with infinite dimensions. This model was later modified by Bradbury (1938) to give an approximate solution for concrete pavement slabs with finite dimensions. To consider geometric configuration of concrete pavements exactly, several numerical models (Chou 1981, Huang 1985) were developed. All these models, either analytical or numerical, were developed in terms of thin plate theory and conventional subgrade models (Winkler foundation or Elastic solid foundation). They do not consider transverse shear deformation of slab and interlocking action in subgrade.

As an improvement, Shi et al (1993) developed an analytical model for analysis of warping stresses in concrete pavements by replacing Winkler foundation with Pasternak foundation (Pasternak 1954). This model was derived in terms of thin plate theory without considering the influence of transverse shear deformation in the slab. In addition, the approximate method of Bradbury (1938) was adopted to represent the finite slab conditions.

To overcome the above limitations, a thick plate model for thermal warping stresses in a concrete pavement slab with four free edges resting on the Pasternak foundation is developed in this paper. First, fundamental equations of this problem is developed based on the Reissner thick plate theory (1945) and the Pasternak foundation model (1954), as well as an assumption that slab temperature varies linearly through its thickness. Second, the solution to the fundamental equations is obtained by superposing the solutions of two elemental slabs (shown in Fig. 1).

Fig. 1: **Superposition of Elemental Slabs for the Slab TA**



Derivation of Fundamental Equations

Incorporating strains induced by variations of temperature, the fundamental equations for a thick plate acted by temperature gradient on the Pasternak foundation are obtained as follows:

$$\nabla^4 w_c - \frac{c^2 k + G_b}{D_1} \nabla^2 w_c + \frac{k}{D_1} w_c = 0 \quad (1a)$$

$$\nabla^4 w_p - \frac{c^2 k + G_b}{D_1} \nabla^2 w_p + \frac{k}{D_1} w_p = \frac{c^2}{D_1} \nabla^2 q - \frac{q}{D_1} \quad (1b)$$

$$\frac{h^2}{10}\nabla^2\psi - \psi = 0 \tag{1c}$$

$$Q_{xp} = Q_x^* + \frac{\partial}{\partial x}(-D_1\nabla^2 w_c + c^2 k w_c) \tag{1d}$$

$$Q_{yp} = Q_y^* + \frac{\partial}{\partial y}(-D_1\nabla^2 w_c + c^2 k w_c) \tag{1e}$$

in which Q_x^* and Q_y^* are functions which must satisfy the following equations

$$\frac{h^2}{10}\nabla^2 Q_x^* - Q_x^* = D_2\frac{\partial}{\partial x}(\nabla^2 w_p) - \frac{h^2}{10(1-\mu)}\frac{\partial}{\partial x}(q + k w_p) \tag{2a}$$

$$\frac{h^2}{10}\nabla^2 Q_y^* - Q_y^* = D_2\frac{\partial}{\partial y}(\nabla^2 w_p) - \frac{h^2}{10(1-\mu)}\frac{\partial}{\partial y}(q + k w_p) \tag{2b}$$

For a rectangular plate, the complementary functions can be found from Eqs. (1a) to (1c), and the constants of integration associated with these can be evaluated from the twelve boundary conditions that can be developed from the four edges of the plate.

Solution of the Elemental Slab TE1

Based on the boundary conditions of the elemental SLAB TE1 (Fig. 1), the solutions of SLAB TE1 with unknown coefficient E_m can be obtained from the fundamental equations as follows:

$$w = \sum_{m=0,2}^{\infty}\frac{E_m}{D_1\Delta_m}[\Delta_{m1}cc(y) + \Delta_{m2}ss(y)](-1)^{m/2}\cos(\frac{m\pi}{a}x) \tag{3a}$$

$$Q_x = \sum_{m=0,2}^{\infty}\frac{E_m}{\Delta_m}\{-\frac{m\pi}{a}[(I_{m1}\Delta_{m1} - I_{m2}\Delta_{m2})cc(y) + (I_{m1}\Delta_{m2} + I_{m2}\Delta_{m1})ss(y)] + \Delta_{m3}\beta_m\cosh(\beta_m y)\}(-1)^{m/2}\sin(\frac{m\pi}{a}x) \tag{3b}$$

$$Q_y = \sum_{m=0,2}^{\infty}\frac{E_m}{\Delta_m}[(I_{m3}\Delta_{m2} + I_{m4}\Delta_{m1})cs(y) + (I_{m3}\Delta_{m1} - I_{m4}\Delta_{m2})sc(y) - \frac{m\pi}{a}\Delta_{m3}\sinh(\beta_m y)](-1)^{m/2}\cos(\frac{m\pi}{a}x) \tag{3c}$$

$$M_x = M_T + \sum_{m=0,2}^{\infty}\frac{E_m}{\Delta_m}[(I_{m5}\Delta_{m1} + I_{m6}\Delta_{m2})cc(y) + (I_{m5}\Delta_{m2} - I_{m6}\Delta_{m1})ss(y) + I_{m7}\Delta_{m3}\cosh(\beta_m y)](-1)^{m/2}\cos(\frac{m\pi}{a}x) \tag{3d}$$

$$M_y = M_T + \sum_{m=0,2}^{\infty}\frac{E_m}{\Delta_m}[(I_{m8}\Delta_{m1} - I_{m9}\Delta_{m2})cc(y) + (I_{m8}\Delta_{m2} + I_{m9}\Delta_{m1})ss(y) - I_{m7}\Delta_{m3}\cosh(\beta_m y)](-1)^{m/2}\cos(\frac{m\pi}{a}x) \tag{3e}$$

$$M_{xy} = \sum_{m=0,2}^{\infty}\frac{E_m}{\Delta_m}[(I_{m10}\Delta_{m2} - I_{m11}\Delta_{m1})cs(y) + (I_{m10}\Delta_{m1} + I_{m11}\Delta_{m2})sc(y) + I_{n12}\Delta_{m3}\sinh(\beta_m y)](-1)^{m/2}\sin(\frac{m\pi}{a}x) \tag{3f}$$

$$p = \sum_{m=0,2}^{\infty}\frac{E_m}{D_1\Delta_m}[(I_{m13}\Delta_{m1} - I_{m14}\Delta_{m2})cc(y) + (I_{m13}\Delta_{m2} + I_{m14}\Delta_{m1})ss(y)](-1)^{m/2}\cos(\frac{m\pi}{a}x) \tag{3g}$$

Solution of the Elemental Slab TE2

Similar to the elemental SLAB TE1, the solutions of SLAB TE2 with unknown coefficient F_n can be obtained as follows:

$$w = \sum_{n=0,2}^{\infty}\frac{F_n}{D_1\Delta_n}[\Delta_{n11}cc(x) + \Delta_{n12}ss(x)](-1)^{n/2}\cos(\frac{n\pi}{b}y) \tag{4a}$$

$$Q_y = \sum_{n=0,2}^{\infty}\frac{F_n}{\Delta_n}\{-\frac{n\pi}{b}[(I_{n1}\Delta_{n11} - I_{n2}\Delta_{n12})cc(x) + (I_{n1}\Delta_{n12} + I_{n2}\Delta_{n11})ss(x)] - \Delta_{n13}\beta_n\cosh(\beta_n x)\}(-1)^{n/2}\sin(\frac{n\pi}{b}y) \tag{4b}$$

$$Q_x = \sum_{n=0,2}^{\infty}\frac{F_n}{\Delta_n}[(I_{n3}\Delta_{n12} + I_{n4}\Delta_{n11})cs(x) + (I_{n3}\Delta_{n11} - I_{n4}\Delta_{n12})sc(x) + \frac{n\pi}{b}\Delta_{n13}\sinh(\beta_n x)](-1)^{n/2}\cos(\frac{n\pi}{b}y) \tag{4c}$$

$$M_y = M_T + \sum_{n=0,2}^{\infty}\frac{F_n}{\Delta_n}[(I_{n5}\Delta_{n11} + I_{n6}\Delta_{n12})cc(x) + (I_{n5}\Delta_{n12} - I_{n6}\Delta_{n11})ss(x) - I_{n7}\Delta_{n13}\cosh(\beta_n x)](-1)^{n/2}\cos(\frac{n\pi}{b}y) \tag{4d}$$

$$M_x = M_T + \sum_{n=0,2}^{\infty}\frac{F_n}{\Delta_n}[(I_{n8}\Delta_{n11} - I_{n9}\Delta_{n12})cc(x) + (I_{n8}\Delta_{n12} + I_{n9}\Delta_{n11})ss(x) + I_{n7}\Delta_{n13}\cosh(\beta_n x)](-1)^{n/2}\cos(\frac{n\pi}{b}y) \tag{4e}$$

$$M_{xy} = \sum_{n=0,2}^{\infty}\frac{F_n}{\Delta_n}[(I_{n10}\Delta_{n12} - I_{n11}\Delta_{n11})cs(x) + (I_{n10}\Delta_{n11} + I_{n11}\Delta_{n12})sc(x) - I_{n12}\Delta_{n13}\sinh(\beta_n x)](-1)^{n/2}\sin(\frac{n\pi}{b}y) \tag{4f}$$

$$p = \sum_{n=0,2}^{\infty}\frac{F_n}{D_1\Delta_n}[(I_{n13}\Delta_{n11} - I_{n14}\Delta_{n12})cc(x) + (I_{n13}\Delta_{n12} + I_{n14}\Delta_{n11})ss(x)](-1)^{n/2}\cos(\frac{n\pi}{b}y) \tag{4g}$$

Determination of Unknown Coefficients

After superposing the solutions of the two elemental slabs into the boundary conditions of the Slab TA, the following linear equation set can be obtained,

$$\sum_{n=0,2}^{\infty}\sum_{m=0,2}^{\infty}(-1)^{n/2}T_{mn}E_m\cos(\frac{n\pi}{b}y) + \sum_{n=0,2}^{\infty}(-1)^{n/2}F_n\cos(\frac{n\pi}{b}y) + 2M_T = 0 \tag{5a}$$

$$\sum_{m=0,2}^{\infty}\sum_{n=0,2}^{\infty}(-1)^{m/2}U_{mn}F_n\cos(\frac{m\pi}{a}x) + \sum_{m=0,2}^{\infty}(-1)^{m/2}E_m\cos(\frac{m\pi}{a}x) + 2M_T = 0 \tag{5b}$$

From Eqs (8a) and (8b), the unknown coefficients E_m and F_n can be determined.

Solution of SLAB TA

Solution for Slab TA can be obtained by superposing the solutions of the elemental SLAB TE1 and TE2 as follows:

$$w = (w)_{TE1} + (w)_{TE2} \tag{6a}$$

$$Q_x = (Q_x)_{TE2} \tag{6b}$$

$$Q_y = (Q_y)_{TE1} \tag{6c}$$

$$M_x = (M_x)_{TE1} + (M_x)_{TE2} \tag{6d}$$

$$M_y = (M_y)_{TE1} + (M_y)_{TE2} \tag{6e}$$

$$M_{xy} = 0 \tag{6f}$$

$$p = (p)_{TE1} + (p)_{TE2} \tag{6g}$$

Thermal warping stresses σ_x and σ_y in the slab TA can be then determined by as follows,

$$\sigma_x = \frac{6[(M_x)_{TE1} + (M_x)_{TE2}]}{h^2} \tag{7a}$$

$$\sigma_y = \frac{6[(M_y)_{TE1} + (M_y)_{TE2}]}{h^2} \tag{7b}$$

Comparison of the Proposed Thick Plate Model with the Thin Plate Model

A rectangular slab with width of 3.5 m is analysed in this section by the proposed thick plate model and the thin plate model (Shi et al, 1993). The problem parameters are: E = 20000 MPa, μ = 0.15, k = 200 MN/m^3, $\Delta T/h$ = 80°C/m, α_t = 0.00001 m/m/°C. The maximum interior warping stress, maximum edge warping stress along the length of the slab and maximum warping stress along the width of the slab determined by these two models are compared to examine the limitations of the thin plate model.

The computed maximum interior warping stresses for the analysed slab with different lengths and thicknesses are listed in Tables 1. Errors of the thin plate model computed from the data in Tables 1 are show in Table 2. Three points can be observed from the results. First, the interior warping stresses corresponding to G_b = 17500 MN/m^3, computed either by the thick plate model or the thin plate model, are always smaller than those corresponding to G_b = 0. This confirms the point that ignoring subgrade interlocking action (the case of Winkler foundation) results in overestimation of the interior warping stresses in slabs. Second, the interior warping stresses determined by the thin plate model are very close to those determined by the thick plate model when the slab in thin. For example, the maximum error of the thin plate model is only 1.3% (Table 2) when the slab thickness is equal to 20 cm. Third, errors of the thin plate model increase as the thickness of slab increases due to the following two shortcomings of the thin plate model: approximation involved in superposition of the solutions of two semi-infinite slabs, and ignoring of the transverse shear deformation of slab. The maximum error of the thin plate model for interior warping stresses is about 7% (Table 2).

The computed maximum edge warping stresses along the length of the analysed slab with different lengths and thicknesses are listed in Table 3. Errors of the thin plate model computed from the data in Table 3 are shown in Table 4. Three observations can be made. First, the maximum edge warping stresses along the length of the slab corresponding to G_b = 17500 MN/m^3, computed either by the thick plate model or the thin plate model, are always smaller than those corresponding to G_b = 0. This confirms that ignoring subgrade interlocking action (the case of Winkler foundation) results in overestimation of the maximum edge warping stresses along the length of the slab. Second, the

Table 1: **Interior Warping Stresses (MPa)**

a) Thin Plate Model

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	1.9099	2.0270	1.9881	1.9294
	17.5	1.7812	1.9375	1.9405	1.9084
30	0	2.0515	2.6734	2.9051	2.9288
	17.5	1.9519	2.5627	2.8145	2.8667
40	0	1.7292	2.7440	3.3965	3.6974
	17.5	1.6758	2.6570	3.3030	3.6164
50	0	1.3424	2.4730	3.4808	4.1378
	17.5	1.3165	2.4165	3.4027	4.0564

b) Thick Plate Model

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	1.8983	2.0297	1.9926	1.9322
	17.5	1.7589	1.9326	1.9404	1.9084
30	0	1.9884	2.6389	2.8859	2.9168
	17.5	1.8820	2.5211	2.7897	2.8506
40	0	1.6444	2.6738	3.3383	3.6494
	17.5	1.5869	2.5818	3.2407	3.5654
50	0	1.2638	2.3929	3.3972	4.0551
	17.5	1.2349	2.3320	3.3154	3.9713

Table 2: **Error (%) of the Thin Plate Model for Interior Warping Stresses**

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	0.6	0.1	0.2	0.1
	17.5	1.3	0.3	0.0	0.0
30	0	3.2	1.3	0.7	0.4
	17.5	3.7	1.7	0.9	0.6
40	0	5.2	2.6	1.7	1.3
	17.5	5.6	2.9	1.9	1.4
50	0	6.2	3.3	2.5	2.0
	17.5	6.6	3.6	2.6	2.1

maximum edge warping stresses along the length of the slab determined by the thin plate model are very close to those determined by the thick plate model when the slab is thin. For example, the maximum error of the thin plate model is only 2.8% (Table 4) when the slab thickness is equal to 20 cm. Third, errors of the thin plate model increase significantly as the thickness of slab increases, due to the same two shortcomings of the thin plate model quoted in the preceding paragraph. The maximum error of the thin plate model for the maximum edge warping stresses along the length of a slab can reach 9.5% (Table 4).

The computed maximum edge warping stresses along the width of the analysed slab with different lengths and thicknesses are listed in Table 5. Errors of the thin plate model computed from the data in Table 5 are shown in Table 6. Three observations can be made. First, the maximum edge warping stresses along the width of the slab corresponding to G_b = 17500 MN/m^3, computed either by the thick plate model or the thin plate model, are always smaller than those corresponding to G_b = 0. This confirms that ignoring subgrade interlocking action (the case of Winkler foundation) results in overestimation of the maximum edge warping stresses along the width of a slab. Second,

Table 3: **Maximum Edge Warping Stresses (MPa) along Length of the Slab**

a) Thin Plate Model

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	1.6608	1.7779	1.7390	1.6803
	17.5	1.5489	1.7052	1.7081	1.6760
30	0	1.7839	2.4058	2.6375	2.6612
	17.5	1.6973	2.3081	2.5599	2.6121
40	0	1.5036	2.5184	3.1709	3.4718
	17.5	1.4572	2.4385	3.0844	3.3978
50	0	1.1673	2.2979	3.3057	3.9627
	17.5	1.1448	2.2448	3.2310	3.8847

b) Thick Plate Model

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	1.6256	1.7529	1.7134	1.6514
	17.5	1.5059	1.6754	1.6808	1.6472
30	0	1.6989	2.3426	2.5857	2.6142
	17.5	1.6078	2.2405	2.5053	2.5637
40	0	1.3944	2.4224	3.0824	3.3905
	17.5	1.3503	2.3392	2.9937	3.3155
50	0	1.0698	2.1945	3.1946	3.8497
	17.5	1.0452	2.1382	3.1176	3.7706

Table 4: **Error (%) of the Thin Plate Model for Maximum Edge Warping Stresses along the Length of the Slab**

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	2.2	1.4	1.5	1.8
	17.5	2.8	1.8	1.6	1.7
30	0	5.0	2.7	2.0	1.8
	17.5	5.6	3.0	2.2	1.9
40	0	7.4	4.0	2.9	2.4
	17.5	7.9	4.2	3.0	2.5
50	0	9.1	4.7	3.5	2.9
	17.5	9.5	5.0	3.6	3.0

the maximum edge warping stresses along the width of a slab determined by the thin plate model are very close to those determined by the thick plate model when the slab is thin. For example, the maximum error of the thin plate model is only 3.0% (Table 6) when the slab thickness is equal to 20 cm. Third, errors of the thin plate model increase dramatically as the thickness of slab increases, due to the same two shortcomings of the thin plate model quoted in the preceding paragraph. The maximum error of the thin plate model for the maximum edge warping stresses along the width of slab can reach 31.5% (Table 6).

Summary

A thick plate model for thermal warping stress in concrete pavements was developed using the Reissner thick plate theory and the Pasternak foundation model, which considers not only interlocking action of subgrade but also transverse shear deformation of slab. Using the proposed thick plate model, the limitations of the thin plate

Table 5: **Maximum Edge Warping Stresses (MPa) along Width of the Slab**

a) Thin Plate Model

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	1.6608	1.6608	1.6608	1.6608
	17.5	1.5489	1.5489	1.5489	1.5489
30	0	1.7839	1.7839	1.7839	1.7839
	17.5	1.6973	1.6973	1.6973	1.6973
40	0	1.5036	1.5036	1.5036	1.5036
	17.5	1.4572	1.4572	1.4572	1.4572
50	0	1.1673	1.1673	1.1673	1.1673
	17.5	1.1448	1.1448	1.1448	1.1448

b) Thick Plate Model

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	1.6256	1.6262	1.6265	1.6266
	17.5	1.5059	1.5045	1.5037	1.5031
30	0	1.6989	1.6825	1.6733	1.6675
	17.5	1.6078	1.5893	1.5785	1.5716
40	0	1.3944	1.3516	1.3180	1.2970
	17.5	1.3503	1.3025	1.2682	1.2461
50	0	1.0698	1.0009	0.9388	0.8942
	17.5	1.0452	0.9775	0.9159	0.8709

Table 6: **Error (%) of the Thin Plate Model for Maximum Edge Warping Stresses along the Width of the Slab**

Thickness (cm)	G_h (MN/m)	Length (m) 3.5	4.5	5.5	6.5
20	0	2.2	2.1	2.1	2.1
	17.5	2.9	2.8	3.0	3.0
30	0	5.0	6.0	6.6	7.0
	17.5	5.6	6.8	7.5	8.0
40	0	7.4	11.2	14.1	15.9
	17.5	7.9	11.9	14.9	16.9
50	0	9.1	16.6	24.3	30.5
	17.5	9.5	17.1	25.0	31.5

model were investigated, and some conclusions can be drawn as follows:

- Subgrade interlocking action has significant influence on warping stresses in slabs. Ignoring this action results in overestimation of the slab warping stresses.
- The use of thin plate model does not affect interior warping stresses of a slab significantly, giving a maximum error of about 6.6%. The thin plate model can be used to estimate interior warping stresses for concrete pavement slabs in the normal range of slab sizes and thicknesses.
- The use of thin plate model affects edge warping stresses of a slab significantly, giving maximum errors of 9.5% and 31.5% for edge warping stresses along the length and width of a slab respectively. The thin plate model is not suitable for use in estimating edge warping stresses of concrete pavement slab and the thick plate model is recommended for this purpose.

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CONTRACT ROAD MAINTENANCE IN AUSTRALASIA: A REVIEW

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Introduction

Road maintenance in Australia and New Zealand had until the turn of the decade traditionally been undertaken directly by the responsible authority with minimal contracting out of services. Where services had been contracted out, they tended to be for major or specific items such as asphalt surfacing, bitumen spraying, line marking or plant hire.

In the early to mid 1990's, an era of a tightening economic climate and "smaller government", there was a continuing drive to ensure effectiveness and efficiency in the allocation of road funding to maintain what is becoming a very mature road network. Within this climate there was seen a demand by Government Authorities for the introduction of new management systems such as Pavement Management Systems and Maintenance Management Systems. We have also seen recent trials of new structures for delivery of maintenance, with an emphasis on contracting-out to achieve competition.

This paper seeks to outline current practices in developing road maintenance by contract, especially in Australia and New Zealand. It is adapted, and updated, from a paper prepared for the Roads & Traffic Authority NSW and would not have been possible without the close cooperation of staff of all the Australasian Road Authorities together with their colleagues in UK, USA and Canada.

Glossary of Terms

One of the problems in the preparation of a paper of this type is the diversity of terms used for the same activity by different countries and even by different states within the one country. As far as possible the authors have attempted to use standard terms throughout the document.

The following meanings of these terms generally apply unless the content indicates otherwise:

- **Routine Maintenance** - ongoing maintenance which involves all of the road assets. Items include crack filling, pothole repair, grading of unsealed shoulders and vegetation control.
- **Period or Specific Maintenance** - preservation and rehabilitation maintenance which is carried out from time to time on specific assets at specific locations such as sprayed bitumen reseals, surface correction, shoulder reconditioning and linemarking.
- **Rehabilitation or Restoration** - programmed asset enhancement work such as granular pavement overlays, structural asphalt overlays, pavement resheeting and recycling.
- **Contract Road Maintenance** - refers to all work undertaken under contract by private contractors or corporatised government agencies; may include plant hire contracts.
- **Direct Control** - where the work is undertaken by employees of the owner on a day works basis.
- **Schedule of Rates Contract** - where the contractor has provided a rate or rates to undertake work and is paid for the actual quantity of work done.

- **Lump Sum Contract** - where the contractor provides a price to undertake the work regardless of the actual quantity of work performed.

- **Term or Period Contract** - where the contractor is engaged to undertake the work over a fixed period of time, usually one or more years; may be schedule of rates or lump sum and include routine, specific and restoration work.

- **Performance Contract (Short Term)** - where the contractor is required to design the treatment to meet specified performance criteria for the completed work (e.g. must be designed for a particular traffic loading, design life, end point specification and the like).

- **Performance Contract (Long Term)** - where the contractor is engaged to manage and maintain the network and is required to meet general network performance criteria (e.g. rideability) over a significant period of time and return the network to the owner at the end of the contract period in a minimum specified condition.

- **Geographical Area Contract** - where the contractor is engaged to undertake the work on a defined road network. Contract may be lump sum, schedule of rates or period.

- **Owner** - organisation responsible for the overall performance of the road network, often including the preparation of rehabilitation programmes; usually the relevant Road Authority;

- **(Project) Manager** - organisation responsible for managing the maintenance of the network on a planned basis; usually part of the Road Authority structure, or a consultant;

- **Service Provider** - organisation responsible for undertaking the maintenance; usually either part of the Road Authority or a Contractor.

The Australian Situation

The Australian Road Network is a complex one maintained by State Road Authorities and Local Authorities using National, State and Local Authority funding. This review is essentially restricted to the State and Territory Road Authorities.

Roads and Traffic Authority, New South Wales

Sydney

Sydney Region has pioneered most of the contract road maintenance developments in Australia in the last five years.

Initially three different procedures were trialed, namely:

- A contract network with a consultant project manager, and a contractor maintaining the network.

- A works centre network with a consultant as project manager, and the RTA works office working as a contractor.

- A base network with no change from existing day labour practices.

In the case of both the contract network and the works centre network all work was initiated by a Site Instruction. The Site Instruction is prepared by the Project Manager and specifies the work to be performed and applicable pay items from a Schedule of Rates. No work is to be undertaken unless a Site Instruction has been issued. Hence, there is no need for routine road patrols. The Project Manager initiates work in accordance with the Code of Practice in order to maintain uniform intervention levels. The Code is based assessment of need on road condition and road hierarchy (i.e. traffic volume and importance).

Full details of the trial are provided by Smith, Frost and Foster (1994 a,b).

The road maintenance contract pilot had short and long term impacts on the operation of the Sydney Region. Significant savings in excess of 25% have been claimed (see Smith et al. 1994 a,b). Due to both the changes in administration of road maintenance and its method of delivery suggested by the trial there have been significant short term and long term effects on the delivery of road maintenance in the Sydney Region.

The maintenance organisation in the regional structure is totally based on the contractual structure and relationships implemented for the pilot. Three distinct organisation units have been established, emulating the roles of the Region's Road Asset Unit, the private sector maintenance manager and the contractor. This ensures that the Region's maintenance operations are managed in a competitive manner which provides for the ongoing evaluation of performance. Private and

public sector resources have been placed on a similar operational basis, so that the appropriate mix of private and public sector resources may be established, monitored and reviewed.

In 1995 the RTA engaged a private sector organisation to manage and maintain the full range of assets on part of the network (approx. 2000 lane km) for a 10-year period on a full performance basis. Performance of the contract will be measured in terms of the change condition of the assets over the life of the contract.

The two networks which were part of the initial pilot will continue to be administered on a schedule of rates basis with the continued separation of roles between the Project Manager and Service Provider.

Other Regions

The RTA NSW is decentralised into four regions. Western Region is rural, Northern Region includes Newcastle, Southern Region includes Wollongong and Sydney Region covers the greater metropolitan area. There are marked differences between the methods of maintenance delivery in Sydney and the rest of the state.

The management and project management functions in the three rural Regions are performed by RTA engineers in Zones, District and Depots. Specific tasks are let to contract if contractors can deliver a similar quality product for a better price, or when RTA resources or expertise are not available. Major rehabilitation tasks are often the subject of minor or major contracts. As the RTA workforce continues to be reduced the reliance on external resources for both service provision and project management is likely to increase.

Queensland Transport

Approximately 50% of the total Queensland Transport (QT) expenditure on road maintenance is spent by Local Authorities on declared roads as Agents for the Department. This maintenance is comprised routine maintenance tasks such as mowing, pot hole repair etc. and special maintenance which covers more major type works such as reseals and asphalt overlays (Caldwell, 1994).

In the past Local Authorities as well as the QT day labour maintenance crews have been reimbursed on an agency basis for the maintenance works they undertake. QT has developed documentation for road maintenance performance contracts (agreements) which have replaced the previous agency-based agreements. This means that the service provider must meet the agreed performance levels for the agreed allocation.

The Department undertook a trial of maintenance by contract in the Gympie district in 1992. A total network of approximately 660 carriageway km was involved. All three network operators (a contractor, Cooloola Shire and the Department's day labour crews) reported to the consultant Project Manager.

The contract was a combination of lump sum for routine maintenance and schedule of rates for specific maintenance. Most major activities were generally in the form of schedules of rates. This allowed the Project Manager to have some control over the budget, in that the quantity of schedule of rates work can be varied.

Queensland Transport favours the Road Maintenance Performance Contract approach with their traditional suppliers of maintenance services rather than the open competition approach. The open competition approach is used where the Local Authority does not desire to enter into a Road Maintenance Performance Contract.

Department of Transport & Works, Northern Territory

Prior to 1990, maintenance was undertaken by day labour (Hornsby, 1990). At this stage the Northern Territory Government proceeded to maximise private sector involvement. This policy has resulted in the gradual demise of the day labour work force.

The transition to contract maintenance was undertaken over several years. The most recent contracts have been introduced to replace the mainly manual tasks previously performed by day labour staff. Some elements of this work (e.g. pothole patching, minor road repairs and clean up works) still require too much direction and supervision by Government supervisors. This is being addressed by setting up "patrol" activities by contractors to identify and attend to minor defects (Hornsby, 1994).

The current situation is quite different from the situation described by Hornsby in 1990 where part of the work was done on a plant hire type basis with a significant amount of management input.

Contracts apply for all Northern Territory Government Transport Infrastructure assets

including roads, airstrips, marine facilities and associated buildings. Generally the contracts are:

- Schedules of Rates contracts for both period contract and specific rehabilitation works.
- Packaged so that they suit regional and sub-regional boundaries.

Period contracts are generally let for an initial 12-month term with the option to extend for a further two 12-month periods.

Presently most contract administration is vested in the NT Government Construction Agency on an untied consultancy basis. Private consultants can be used if the Agency does not have the experience or capacity to administer certain types of contracts.

Department of Transport, Tasmania

The Department of Transport, Tasmania has undergone several changes of structure during the last few years. In essence the trend has been towards a management group and a day labour force (Works Tasmania). Works Tasmania was corporatised from 1 July 1994.

As of late 1994, maintenance other than routine maintenance was undertaken by contract usually on a schedule of rates basis. Routine maintenance will increasingly be contracted out.

Vicroads

Contracts are used in all facets of maintenance on the State Highways and Main Roads.

At present contracts are let for lump sum routine maintenance and schedule of rates periodic maintenance and are site specific lump sum contracts for rehabilitation (Lawton 1994). Performance incentives are provided via use of liquidated damages if the specified performance is not met.

All project management is undertaken in-house and this is likely to continue although consultants may be involved in the future in monitoring and reporting on specific issues requiring evaluation. As contract maintenance is a new and expanding area contractors may engage consultants to provide additional expertise.

Main Roads Department, Western Australia

The Department will engage consultants to project manage two significant road networks in 1996. Contractors will be engaged separately to undertake the maintenance.

Road Transport Agency, South Australia

The Road Transport Agency (RTA SA) has, in the past, contracted out very little routine maintenance operations (1%) but has contracted out the bulk of rehabilitation and preservation works (95%) (Gelston, 1994).

The RTA SA is in the process of implementing a process to allow all road maintenance to be offered for tender. At present these guidelines will only apply to the sealed road network for which the State Government is responsible. Contracts are a mixture of lump sum (for routine maintenance), schedule of rates and day works.

The New Zealand Experience

Background

Transit New Zealand, by an Act proclaimed in 1989, is the Client required to buy services in the marketplace for both professional services and physical works under the Government's Competitive Pricing Procedure (CPP).

Organisation

Transit New Zealand has developed a structure which clearly delineates the role of owner, project manager and service provider. The structure is:

Owner	Transit New Zealand
Manager	Consultant (competitively bid)
Service Provider	Contractor (competitively bid)

Both the manager and service provider may be State Owned Enterprises or Local Trading Enterprises (i.e. corporatised Works Offices) but the work must be won in competition.

The physical works contracts were developed into packages that would

- encourage new entrants into the market, previously the work was undertaken by Stated Owned Enterprises, e.g. Works Civil Construction;
- be large enough to be commercially viable;
- be large enough to ensure that the contractor and consultant could sustain a commitment to development of expertise;
- be small enough to avoid monopolistic situations occurring.

An indication of the sizes and durations of the initial packages is given in Table 1.

Table 1: **Physical Works Package Sizes for State Highway Maintenance**
(After Rendall, 1992)

Scope	Area	Initial Contract Duration
Pavement and Drainage Maintenance and Emergency Call Outs	Area determined to generate NZ$600,000 to NZ$1,500,000 per annum, per contract	1-2 years increasing to 2-3 years as Transit New Zealand and Contractors gain experience
Signs	Same area as pavement and drainage contract	
Marker Posts, Reflective Pavement Markets, Potholes, Guardrails	Same area as pavement and drainage contract	
Routine Bridge Repairs	Same area as pavement and drainage contract, or larger	Typically 3-5 months
Rest Area and Landscape Maintenance	Areas initially smaller than for other maintenance activities	Typically 1-2 years
Roadmarking	No smaller than pavement and drainage contract, and usually larger	1 years
Traffic Signal Maintenance	One contract for each city with traffic signals	1 or 2 years
Lighting Maintenance	One contract for each centre with lighting (usually each city or population centre)	1-2 years

An exception to the use of small specialised packages was maintenance of motorways where all works are undertaken under the one contract to enable coordination of activities to minimise traffic disruption.

Rendall (1992) has analysed the interim figures for the 1991/92 financial year and has provided a breakdown of highway maintenance costs as shown in Figure 1.

Figure 1: **Highway Maintenance Costs**

Consultant Functions

- Management of the Network
- Investigation, Preparation of Contracts, Supervision/Administration of Physical Works Contracts

NZ$ 22.4M

Contractor Functions

Routine Maintenance

Includes Pavement, drainage, bridges, traffic signals, signs, lighting, etc.

NZ$108.7M

Preventative Maintenance

Includes resealing, asphaltic surfacing, and pavement rehabilitation

NZ$ 78.0M

Total for 11,523km of highway **NZ$209.1M**

Cook (1994) reports that analyses of Transit New Zealand Annual Reports show a 15% reduction in cost due to contract road maintenance.

Management Structures

There has been a trend to separate the owner, management and service provider roles within most Road Authorities within Australasia. This has resulted in a more effective commitment to road maintenance. Maintenance tasks are being documented, maintenance intervention levels determined, and maintenance being planned on a needs basis.

Essentially the management of contract maintenance can be classified into one of five management models (see Table 2). Even those organisations which carry out all maintenance in-house are tending to develop an in-house organisation which is modelled on the concept of separation of the owner, manager and service provider roles within their structure.

The model adopted by the Sydney Region of RTA NSW is at one end of the spectrum with all maintenance tasks only being undertaken on issue of a works instruction from the Project Manager (whether a consultant or in-house). Most Authorities have moved to a structure where maintenance planning is undertaken separate from the service delivery function. In most cases however service delivery for routine maintenance is undertaken by the day labour work force.

Most Authorities agree, and the results of the various studies confirm, that effectiveness of the maintenance operation is improved by separating the network management and service delivery of functions.

In view of the limited funds available it is also clear that all maintenance including routine maintenance should be only undertaken on a needs basis and consideration should be given to preparation of Maintenance Codes of Practice to specify when activities should be undertaken. Such a Code should be based on severity and extent of defects, user safety and traffic volumes.

It would be fair to say, that regardless of whether the service provider is in-house or an external contractor:

> **The split of asset ownership/supervision from service delivery allows a better focus on funding and greater emphasis on needs based rather than resource driven maintenance activities.**

Table 2: **Models of Management of Contract Maintenance**

Model	Description	Advantages	Disadvantages	Example
A	Owner engages Project Manager to manage the network on its behalf. The Service Provider may be a Contractor or in-house organisation and only undertakes work as directed. Manager guided by Code of Practice. Contractor paid for work done.	Maintenance becomes needs and not resource driven. Clear delineation between roles of owner, manager and service provider. Budget can be closely controlled. Manager managing the road network and not the workforce.	Additional supervision costs. Need to develop accurate technical documentation. Need to measure work done. Minor labour intensive maintenance tasks difficult to specify.	• Sydney Region RTA • UK • Some USA
B	As for **A** except Contractor is controlled by Code of Practice for minor maintenance activities. Some of the management role is taken by Contractor.	Maintenance still needs driven but may be less so than **A**. Still clear delineation between Owner and Manager but less clear delineation between Manager and Service Provider. Manager managing the road networks and not the work- force. Less supervision costs than **A**.	As for **A** but less ability to control budget as certain items such as minor labour intensive maintenance is lump sum and tied to the contract's Code of Practice. Tendency for work to become resource driven.	• QT Pilot Study • Transit New Zealand • Tasmania • Northern Territory
C	Owner engages Contractor to undertake management and service provision. Contractor paid for work done.	Budgets controlled.	No independence between Manager and Service Provider. Tendency for work to become resource driven.	British Columbia
D	Owner engages Contractor to manage and maintain network at a specified standard for extended time period.	Responsibility for performance rests with Manager and Service Provider. Allows for more innovative maintenance delivery using financing and technology. Budget level known for extended period.	Latent conditions in an ageing network. What are the performance criteria? How are rewards and risks shared? **Untried.**	Sydney Region 10 year Performance Contract.
E	Owner performs all roles with service provision either in-house or by contract.	Low supervision costs.	Maintenance tends to be resource rather than needs driven. Roles not clearly delineated.	Previously common in Road Authorities throughout the world.

Efficiency and Effectiveness

There is very little available hard evidence on which to make an assessment of the efficiency and effectiveness of contract road maintenance. In fact, a number of authors report that very little economic analysis is undertaken before the decision is made to contract out services. The decision is usually a politically motivated one. Some of the best evidence is available from Australia and New Zealand.

New Zealand

Cook (1992) has analysed the results of the first round of tenders following the change to Competitive Pricing Procedures in 1990 and found a saving of 13% over the previous day labour operations. This may have been due to the circumstances existing at the time, i.e.

" (a) Due to the tight financial climate, quantities of work included in the contracts were, in some instances, reduced to ensure that the estimate and budget coincided.

(b) There was strong competition for all contracts. This was, in part, due to the downturn in the economy."

(Cook 1992, p 274)

In 1994 Cook was able to confirm that Transit New Zealand annual reports show absolute savings of 15% due to the introduction of CPP, despite continuing low inflation (Cook, 1994).

Consultants are engaged to manage the networks but cost savings over the previous system were not able to be quantified due to change in some duties between the contractor and the maintenance manager.

Tasmania

In Tasmania the function of network manager (now Department of Transport) has been separate from the day labour work force (now Works Tasmania) for several years. During 1993 Department of Transport and Works commenced road maintenance, except for routine maintenance, by contract. Giltinan (1994) has reported that overall

there has been a significant reduction in costs (see Table 3).

Table 3: **Comparison between Day Labour & Contract Costs**

	Day Labour Percentage of Total Cost	Contract Percentage of Total Cost
(i) **Maintenance**		
Documentation	2% (limited documentation only required)	4% – 5% (fulldocumentation required)
Supervision		3%
Direct/ Contract Costs	20% to 30% (expected saving by going to contract)	–
(ii) **Reseals/Overlays**		
Documentation	–	2%
Supervision	–	2%
Direct/ Contract Costs	20% (expected saving by going to contract)	–

As can be seen from Table 3, the overall saving on contract maintenance in Tazmania was 15% - 25% and an overall saving on reseals and overlays of 15% by the use of contract.

RTA New South Wales, Sydney Region Pilot Study

The initial evaluation found that the cost of work by the contractor was 16 percent less than the cost of the same work by the RTA, under identical work practices, over the initial six months of the pilot. Over the second six months the cost of work by the contractor was 6 percent more than the cost of the same work by the RTA. This indicates that the RTA work force has improved its productivity by 22 percent through improved management and refined work practices, directly resulting from the exposure to competition under the pilot.

When the contract was re-let in early 1994 there was a further reduction of prices in the order of 15% because the contractor, with experience, was better able to quantify the work required and price it accordingly (Smith et al. 1994 a,b).

Advantages and Disadvantages of Contract and Day Labour Works Programmes

Some of the main advantages and disadvantages of Contract and Day Labour Works Programme and given in Table 4.

Table 4: **Advantages and Disadvantages of Contract and Day Labour Works Programmes**

(After AERCF 1992)

Method	Advantages	Disadvantages
Government Depot Based Work Gangs	Low hourly unit costs due to continuity of work. Ideal repetitive work for skills retention and training. Local knowledge both technical and commercial. Ongoing responsibility for road network therefore higher quality more likely. Design section relates closely to construction section allowing for improvements and efficiencies to be easily made. Plant ownership costs reduced by the statutory avoidance of 20% sales tax on purchases.	Static costs which are difficult to vary to suit change in work load and funding. Reduced commercial incentives for economical performance. Limited career growth for staff leading to skill development stagnation. Difficult to implement innovative ideas in static environment. Cost of time lost in travelling to work site.
Major Works on Day Labour	Total control over work force allowing the necessary degree of attention to be paid to critical areas. e.g. – traffic control – local residents – quality. Employees generally long term employees and generally experienced and trained in works. Generally discount hire rates from depots may be applied to work.	No absolute control of costs. Familiarity within organisation can remove necessary disciplines between design and construction sections. Reduced commercial incentives for economical performance. Disincentives for innovative thinking "why rock the boat". Unproductive work practices and staffing policies may be entrenched.
Depot Based Contractors	Low hourly unit cost due to continuity of work. Ideal repetitive work for skills training and retention. Commercial incentives to perform within budget and to be competitive in market. Driven to be innovative to maintain or improve market position. Client may have a minimum or nil obligation to maintain work therefore allowing for flexibility in spending.	High capital costs for set up which requires some commitment. Quality and general services delivery must be client specified and means established to ensure this occurs. Changes to this and other design may become expensive as they are not valued in a competitive situation. Due to high set up costs with regard to market size there may be insufficient players to ensure proper market operation (several two horse races exist in NSW). Contractor does not have ownership of the network. His responsibility ends at the end of the defects liability period.
Contract Individual Projects	Fixed cost for construction. Tendering system encourages high degree of innovation. Strong commercial incentives for economical performance. Freedom from internal industrial considerations to employ specialist subcontractors for economical completion of specialist segments. If a contractor's industrial relations management is unsatisfactory he (and his work force) loses work without penalty to the road owner.	Difficulty in specifying quality and other areas of service so that tenderers fully understand and are in a position to meet client expectations. Difficulties encountered in client employees being able to delineate between words of contract and client expectation. Contractors responsibility for works ends at end of defects liability project. Contractors work force fluctuates greatly to suit immediate demands leading to reduced opportunities for training and skills retention. Plant and equipment hired or purchased at current market rates – good in recessions, bad in booms.

Conclusions

As can be seen each of the Road Authorities has, or is in the process of introducing, competition into the road maintenance process. There has been a recognition that the separation of the service provision function from the network management function, and the introduction of competition increases the effectiveness of the maintenance task. The greatest area of competition is in the area of service provision with most authorities retaining the management function in-house or delegating it to their Agents.

There is no single agreed management structure. Clearly the structure adopted is dependent on the ability of the Agency to specify and administer the work.

It is hoped that the various Authorities are able to capture data so that they are able to measure objectively the efficiency and effectiveness of their method(s) of service delivery. This information should then become readily available so that others may learn from their experiences and adopt the most appropriate structure. Without such information, decisions about whether or not to introduce competition and the appropriate management structure will continue to be subjective.

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ANALYSIS OF MIXED TRAFFIC AT SIGNALISED INTERSECTIONS

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Abstract: *At-grade intersections are the most common type of road junctions found in India. The knowledge of the capacity of an approach to a controlled intersection is important as it controls the safety, speed and efficiency of the road network. Traffic flow parameters required to estimate capacity of an intersection have been studied worldwide. However, very limited work has been done to relate PCU with traffic and geometric conditions at the site. There are few attempts to calculate practical values of PCU for different categories of vehicles but all of them were for static situations. In the present study, the dynamic nature of PCU has been established by analysing the data of three intersections in Delhi. Variation in PCU values of different vehicle types with parameters like traffic stream composition, saturation flow rate at intersection and approach width has been studied. It is observed that PCU for a vehicle type is controlled by the degree of heterogeneity in the traffic stream. Saturation flow for different approaches was calculated using dynamic PCU values and it has been shown that maximum variation in saturation flow from one cycle to another is reduced to 10% which otherwise may go up to 30 to 40 per cent if PCU values as given by Indian Roads Congress (1990) or Highway Capacity Manual (1985) are adopted. A linear relationship has been established between saturation flow and approach width.*

Introduction

General

Intersection is a place where two or more streets join or cross each other at the same level or at different levels. It is an inevitable part of a road network which governs the safety and efficiency of traffic movement. At-grade intersections are the most common type of road junctions found in India and other developing countries. The traffic flow at controlled intersections is of peculiar type where traffic on each street is periodically halted. Since these intersections are required to process all covering traffic through a common area, a scientific approach is needed for their design. In case of mixed traffic, the efficiency of an intersection decreases sharply with increase of heterogeneity in traffic stream.

Problems of Mixed Traffic

Traffic on Indian roads is heterogeneous in nature. The vehicles range from fast moving cars to animal drawn carts, manually driven bicycles and cycle-rickshaws. The wide variety of vehicles and the disparity in their size and speed create a number of problems at intersections. Because of the low speed of certain types of vehicles, the average speed of the traffic stream drops considerably. It causes enormous delays to other fast moving vehicles. The conflict, confusion and irritation caused by mixed traffic results in a large number of accidents. The mixed mode of traffic not only causes heterogeneity in the traffic flow but also the interaction of a vehicle with another similar or different type of vehicle will be different for different types of vehicles. It will vary with the situations of traffic flow as well. The problems arise out of three major aspects associated with the several types of vehicles in the traffic mix. These are, speed and acceleration capabilities of vehicles, their manoeuverabilities, and lateral clearance requirements within the right of way. In combined flow of such vehicles, a large number of operating conditions are generated which may have to be satisfied in the design. Without careful considerations of these aspects the capacity of the designed facility cannot be fully defined.

Capacity Under Mixed Traffic Conditions

Traffic flow parameters required to estimate capacity of a roadway facility have been studied extensively in western countries. Studies in developed countries have always been with the advantage of homogeneous traffic with very little interference from slow moving vehicles and better law enforcement conditions. In India, there has not been any major effort to develop capacity norms except few scattered attempts to identify some parameters. It is primarily due to the chaotic traffic conditions and poor regulatory system prevailing in urban areas and therefore, evading any systematic study. The capacity calculations of an highway facility under mixed traffic flow becomes difficult because of varying static and dynamic characteristics of vehicles present in the traffic stream.

In the analysis of traffic flow, the various types of vehicles in the stream are converted into a common unit. The most accepted such unit is the passenger car equivalency. Such common unit for each type of vehicle is designed with due consideration of static and dynamic characteristics of the vehicle. Thus, all vehicles of heterogeneous traffic stream are converted into an homogeneous equivalent in terms of passenger car unit (PCU). Traffic engineers normally employ PCU values available as the national standards to calculate capacity of a facility. Any bias in these values will lead to bias in the capacity estimation. Various agencies in India and abroad like Indian Roads Congress (IRC, 1990), Central Road Research Institute (CRRI, 1982), Road Research Laboratory (RRL, 1967), Highway Capacity Manual (HCM, 1965; 1985) have recommended PCU values for different types of vehicle. These PCU values are fixed and must have been derived for a given condition of traffic, roadway and signalisation, while these should depend on all factors affecting the behaviour of a vehicle in the traffic stream. Therefore, a modified approach is needed to be developed considering the various traffic interactions and flow characteristics to have meaningful PCU and thus capacity values.

Passenger Car Unit

The design of a roadway facility is normally dependent on the volume of traffic expected to use the facility. All such facilities are designed for a traffic volume expressed in a common unit called the Passenger Car Unit or PCU. PCU estimates available now are derived from static and uniform operating behaviour of the vehicles. The frequent occurrence of confusion and congestion at urban intersections has been reminding the researchers to suspect the validity of static PCU values. It is observed that in most intersection congestion develops well before the traffic volume grows to a level comparable to its capacity. It happens so due to unrealistic assumption of static PCU values for a dynamic situation of mixed traffic flow. The PCU of a vehicle type represents the number of passenger cars displaced by each vehicle of that type in the traffic stream under specific conditions of flow. The basic consideration behind this concept is that of interference caused by one vehicle to the entire traffic stream. If addition of one vehicle per hour in the traffic stream reduces the average speed of the remaining vehicles by the same amount as the addition of x cars per hour, then one vehicle of that type is considered to be equivalent to x PCUs. The concept of PCU was first introduced in the HCM (1965) for a vehicle stream of cars and a few trucks only, and hence, it is supposed to explain the interaction among the vehicles in a nearly uniform traffic stream. In a mixed traffic situation, the amount of interaction is expected to change with the mix characteristics. Interaction amongst the vehicles is maximum during the saturation flow conditions at intersections. The approach carriageway is congested and space is shared by vehicles depending upon their size, headway and transverse placement. Obviously, the amount of interference produced by different vehicles is different.

Dynamic Passenger Car Unit

It has been established through the research in traffic flow behaviour that the equivalency for a vehicle depends on a large number of factors affecting the stream characteristics. Further, for a given intersection location, parameters such as roadway conditions, control conditions, environmental and climatic conditions remain unchanged for an observation period. Thus, variation in traffic stream characteristics from cycle to cycle in terms of composition and volume must be able to explain the dynamism in the PCU values of different vehicle types. It is hypothesised that dynamic PCU values are related to composition of traffic stream and vehicular characteristics such as relative size and clearing speed under a specified set of roadway and control conditions. This methodology even allows PCU values to be different in the same intersection approach at different times of the day depending upon volume and nature of traffic. On the same account, the PCU value of a type of vehicle can be different at different approaches of the same intersection.

Model Formulation

The concept of dynamic passenger car unit (DPCU) and the related discussion above has given the sound basis for formulating an appropriate model for estimation of dynamic PCU, incorporating the significant traffic flow parameters and stream characteristics. The proposed model is required to incorporate the influence of (i) composition of traffic, (ii) traffic volume that can clear the intersection approach in a green phase, (iii) intersection clearing behaviour of different types of vehicles, and (iv) physical size of the vehicle. Composition accounts for all variations in the mixed traffic and the changed degrees of damaging effect at different volume levels. As the eventual utility of PCU measure is in assessing the throughput of the intersection approach, behaviour of the vehicles in clearing the intersection in terms of speed or time is relevant. Also, the physical size of the vehicle is supposed to indicate manoeuverability, acceleration and deceleration capabilities and space occupancy at the approach and the intersection area which are crucial in the measurement of saturation density. Thus, the clearing speed and vehicle size together account for the intersection occupancy in terms of time and space while composition adds dynamism to it. All vehicular interactions and other intersectional influences culminate in the clearing speed of the vehicles. Also, the size of the vehicle has inverse relationship to clearing speed and ease with which it can negotiate through the intersection. Thus, the passenger car unit for a vehicle is taken directly proportional to speed ratio of the vehicle with respect to car, and inversely proportional to their size (space occupancy) ratio. Mathematically, it can be expressed as given in equation (1).

$$PCU_i = \frac{V_c / V_i}{A_c / A_i} \qquad (1)$$

where PCU_i = Passenger Car Unit of vehicle type i
V_c = clearing speed of car
V_i = clearing speed of vehicle type i and
A_c and A_i = projected area of car and vehicle type i respectively.

While the average projected area for each type of vehicle using the road can be measured easily, clearing speed is required to be modelled for affecting parameters. A vehicle is considered to have cleared the intersection when it crosses the stop line of opposing approach. The clearing speed is a function of composition of traffic and performance of all vehicles at intersection. A submodel was formulated exploring large number of possible dependent relationships for logical validity and statistical soundness. The selected model form is given below.

$$V_i = \sum_{j=1}^{k} a_{i,j} (n_j V_j) + a_{i.m} (1/N) \qquad (2)$$

where V_i = clearing speed of vehicle category i
n_j = number of vehicles of category j clearing the intersection per unit time of green (vpsg) during saturation flow,
k = total number of vehicle categories in the traffic stream.
$a_{i,j}$, $a_{i.m}$ = regression coefficients which represents the effect of j category of vehicle on clearing speed of i category of vehicle, and

$$N = \sum_{j=1}^{K} n_j$$

The PCU model proposed here is fully developed and tested using the data collected at controlled at controlled intersections in Delhi. These are presented in the next section.

Data Collection

The data for this study was collected by video filming a few traffic controlled intersections in New Delhi from a reasonable height so as to cover preferably all and at least two opposing arms of the intersection. Data collected at the following three intersections were used for this study.

(i) Intersection near Nehru Place area

(ii) Intersection near Income Tax Office (ITO)

(iii) Intersection in Shakarpur area

Nehru Place intersection is a four legged right angled junction while ITO junction is a skewed one with heavy traffic on its West-East arm. Shakarpur intersection is a T-shaped controlled by traffic lights. Table 1 gives the details of approach widths and turning movements allowed at different approaches of these intersections.

The recorded film was replayed on a large screen T.V monitor and the required data was then extracted from the film. To make the data amenable and analysis meaningful, all vehicles were grouped into four categories as shown in Table 2.

Table 1: **Physical and Traffic Conditions at Intersections**

Intersection	Approach	Total Width (m)	Right Turn	Effective width of approach for St. Movement (m)
Nehru Place	N – S	9.75	Allowed	6.25
Nehru Place	S – N	10.00	Allowed	6.50
Nehru Place	W – E	7.50	Allowed	4.00
ITO	W – E	14.70	Not Allowed	14.70
Shakarpur	N – S	10.30	Not Allowed	10.30

Table 2: **Classification of Vehicles**

Vehicles	Category	Projected Area (sqm)	Symbol used in Equations
Car, Jeep, Van, Taxi	Car	7.82	c
Truck, Bus, Minibus	Bus	23.00	b
Auto-rickshaw	3-wheeler	3.85	3w
Scooter, Motorbike, Moped, etc.	2-wheeler	1.44	2w

The classified volume counts during saturated portion of the green provided the measurements for composition and flow. For measurement of clearing speeds, 2 - 3 vehicles of a category were randomly taken in the saturated portion of the green and the average time taken by them to clear the intersection was used. The submodels for four categories of vehicles given in Table 2 are as shown in equations (3) to (6).

$$V_c = a_{c.c}\, n_c V_c + a_{c.b}\, n_b V_c + a_{c.3w}\, n_{3w} V_{3w} + a_{c.2w}\, n_{2w} V_{2w} + a_{c.m} (1/N) \quad (3)$$

$$V_b = a_{b.c}\, n_c V_c + a_{b.b}\, n_b V_b + a_{b.3w}\, n_{3w} V_{3w} + a_{b.2w}\, n_{2w} V_{2w} + a_{b.m} (1/N) \quad (4)$$

$$V_{3w} = a_{3w.c}\, n_c V_c + a_{3w.b}\, n_b V_b + a_{3w.3w}\, n_{3w} V_{3w} + a_{3w.2w}\, n_{2w} V_{2w} + a_{3w.m} (1/N) \quad (5)$$

$$V_{2w} = a_{2w.c}\, n_c V_c + a_{2w.b}\, n_b V_b + a_{2w.3w}\, n_{3w} V_{3w} + a_{2w.2w}\, n_{2w} V_{2w} + a_{2w.m} (1/N) \quad (6)$$

where all notations have their usual meaning as explained earlier in equation (2). For example, $a_{c.c}$ in equation (3) represents coefficient $a_{i,j}$ when i and j both are cars. Similarly, in equation (4) $a_{b.3w}$ represents the coefficient when i and j are bus and 3-wheeler respectively. In the absence of the constant term in above equations, the clearing speed should reasonably be explained by the variables incorporated in the relationship. Coefficients of these equations were obtained for each intersection approach through the multiple linear regression analysis technique. Table 3 provides values of these coefficients at three approaches of different widths.

Table 3: **Values of Regression Coefficients**

Approach Width W (m)	Clearing Speed (km / hr)	Coefficient for					R^2 Value
		$n_c V_c$	$n_b V_b$	$n_{3w} V_{3w}$	$n_{2w} V_{2w}$	1/N	
4.0	V_c	0.457	0.317	0.558	0.542	8.663	0.467
	V_b	0.613	1.099	0.693	0.458	6.158	0.321
	V_{3w}	0.397	– 0.461	0.867	0.479	7.713	0.363
	V_{2w}	0.638	0.639	0.366	0.652	7.861	0.511
6.5	V_c	0.688	0.470	0.454	0.471	10.585	0.399
	V_b	0.653	1.103	0.708	0.262	7.777	0.421
	V_{3w}	0.495	0.062	0.858	0.421	8.758	0.395
	V_{2w}	0.328	0.418	0.807	0.785	11.083	0.294
14.7	V_c	0.373	– 0.197	0.195	0.234	25.743	0.598
	V_b	0.526	1.432	0.346	0.132	7.412	0.651
	V_{3w}	0.275	0.504	0.317	0.204	16.358	0.768
	V_{2w}	0.218	– 0.355	0.157	0.335	31.165	0.665

Analysis

Variation in PCU with Traffic Composition

The composition of traffic stream is nothing but the proportion of different types of vehicles in traffic stream. It may change even at the same level of saturation flow rate, N. The observed values of N for through movements at Nehru Place intersection were in the range of 0.8 to 1.4 vehicle per second of effective green (vpsg). Therefore, simultaneous equations (3) to (6) were solved for a fixed value of saturation flow rate (N = 1.0 vehicles per second of effective green) and varying proportions of each vehicle type. Since the clearing speed of a vehicle type is very sensitive to the chosen variables, Gauss-Sidel method was used to solve the simultaneous equations. PCU values for each vehicle type were then calculated using equation (1). Figure 1 shows the variation in PCU for 2-wheeler with composition of traffic stream at Nehru Place intersection. These curves have been drawn for fixed proportion of Car and Bus together as 50 per cent, while 2-wheeler and 3-wheeler proportion contributes the remaining 50 per cent in a complementary manner. The fixed 50 per cent of Car and Bus is also varied in a complementary fashion to generate nine curves as shown in Figure 1(a). Similar curves showing the variation in PCU value of 2-wheeler for fixed

Figure 1(a): **Variation of PCU for 2-Wheeler with Composition at Nehru Place Intersection**

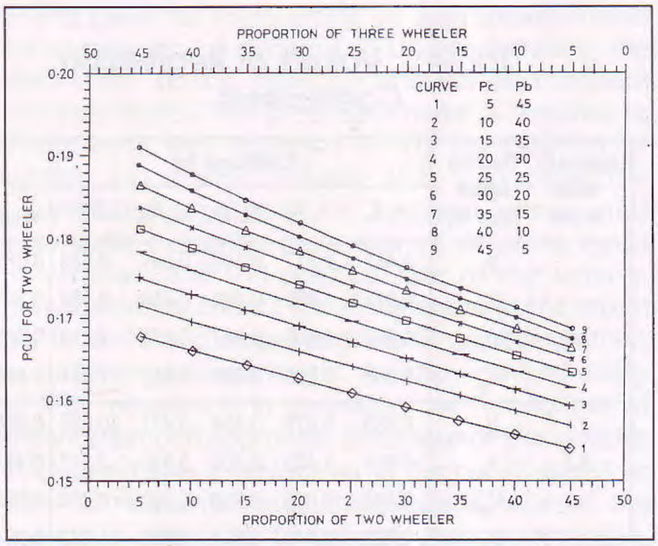


Figure 1(b): **Variation in PCU for 2-Wheeler with Traffic Composition at Nehru Place Intersection**

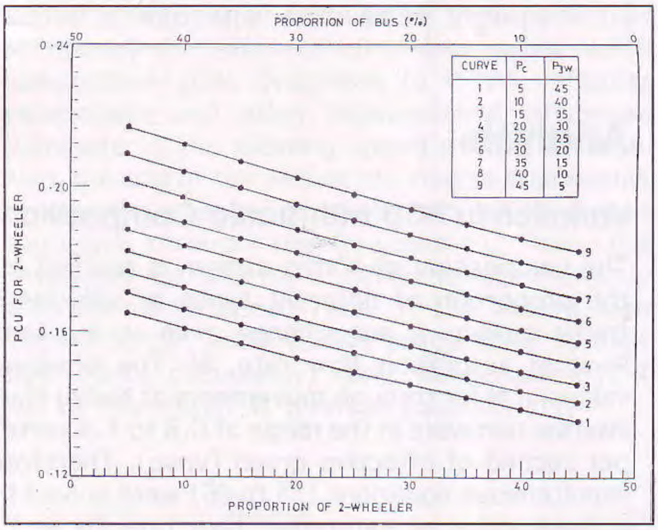


Figure 1(c): **Variation in PCU for 2-Wheeler with Traffic Composition at Nehru Place Intersection**

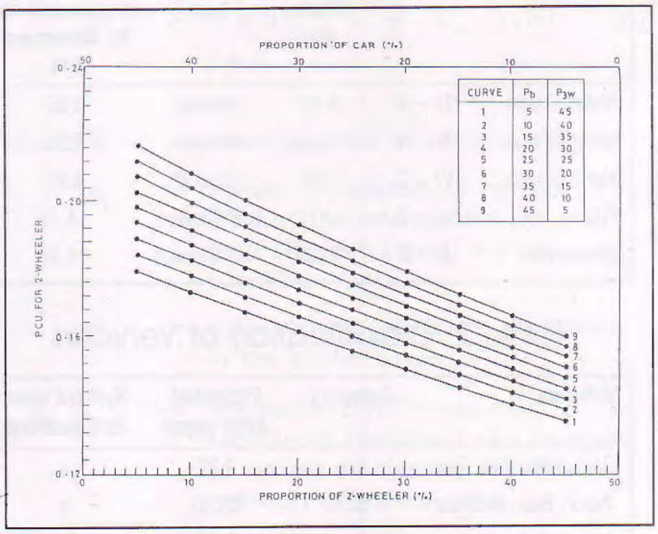
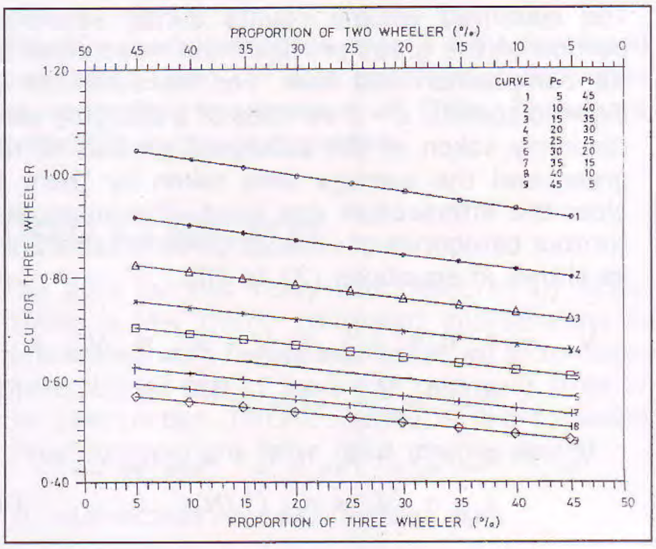


Figure 2: **Variation of PCU for 3-Wheeler with Composition at Nehru Place Intersection**



proportion of Car and 3-wheeler and for fixed proportion of Bus and 3-wheeler are shown in Figure 1(b) and 1(c) respectively. These three sets cover the complete ranges of possible variations and would suggest a PCU for any composition level. Figures 2 and 3 represent similar curves in relation to variation of PCU values for 3-wheeler and Bus respectively.

Curves developed to show variations in PCU values indicate that PCU value for a vehicle category decreases with increase in its own proportion in traffic stream. This is in conformity with the findings of Branston (1979), Miller (1969), Smeed and Hillier (1965) and Webster & Scraggs (1964) who have also reported the same trend. Further, it is observed that PCU for Bus (Fig. 3), at a given proportion of its own, increases with increasing proportion of 2-wheelers (or decreasing proportion of cars). This may be due to the fact that as the proportion of small sized vehicles increases in the traffic stream, heterogeneity increases resulting in more speed differential and therefore, higher PCU values for Bus. Similarly, PCU for 2-wheeler (Fig. 1(a) to 1(c)) increases with increasing proportion of cars. This can also be explained on the basis of homogeneity and heterogeneity in the traffic stream. Moreover, increase in proportion of one type of vehicle is accompanied by decrease in proportion of other vehicle types in the traffic stream which directly affects the homogeneity of heterogeneity of the traffic depending upon net percentages of large and small size vehicles. Thus, even with increase in proportion of larger vehicles,

Figure 3: **Variation in PCU for Bus with Composition at Nehru Place Intersection**

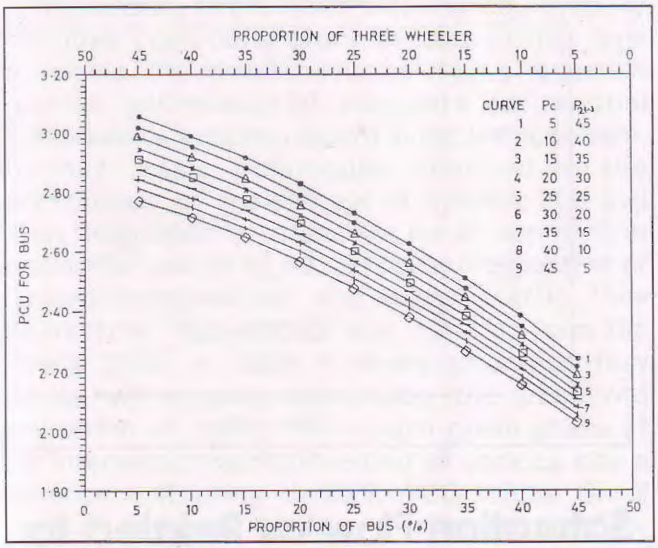
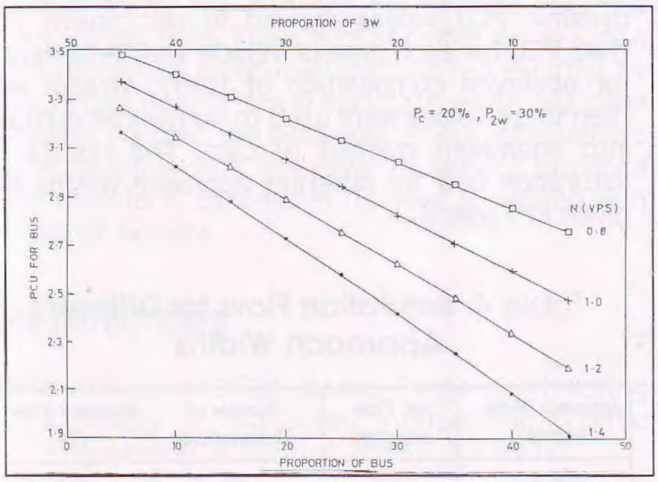


Figure 4: **Variation in PCU for Bus with Saturation Flow Rate**



depending on the overall proportions of traffic mix, the PCU for a large vehicle like Bus may not increase in the same proportion. This trend is reflected in Figure 3 where vertical spacing between the curves is maximum when proportion of bus in traffic stream is only 5 per cent, and reduces uniformly as it increase to 45 per cent.

Variation in PCU with Saturation Flow Rate (N)

Saturation flow rate is the maximum rate of flow of vehicles that can pass through the intersection per unit time of effective green. In addition to other parameters of geometry and control, its value will depend on composition of traffic stream. Composition is the proportion of different types of vehicles in stream. It may be the same even at different values of saturation flow rate, N. Change

Figure 5: **Variation in PCU for 2-Wheeler with Saturation Flow Rate**

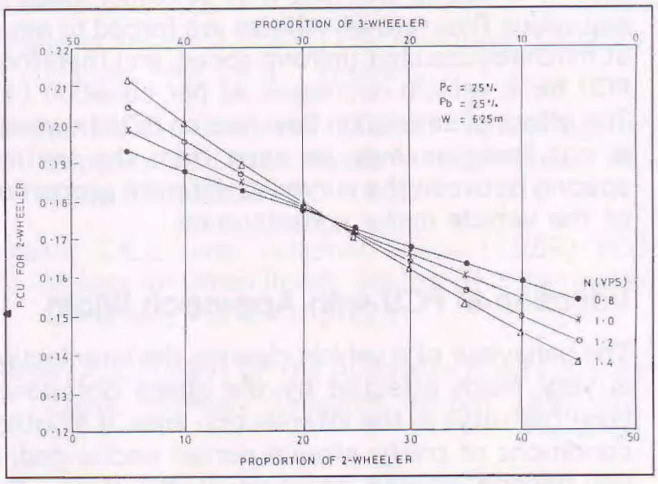
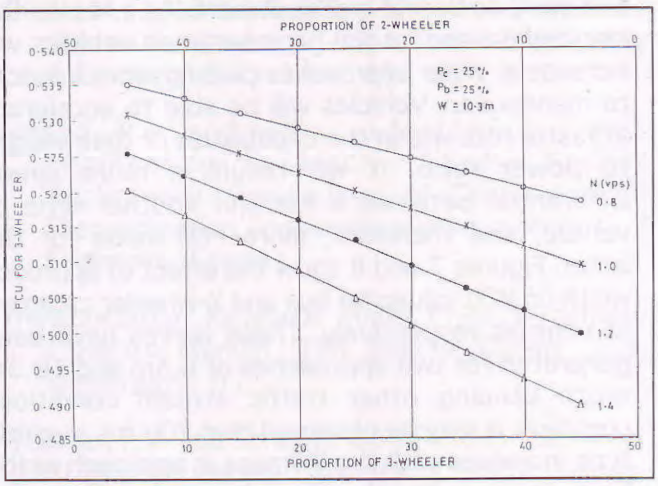


Figure 6: **Variation in PCU for 3-Wheeler with Saturation Flow Rate**



in saturation flow rate, however, will affect the operational characteristics of traffic stream for a given approach width. To study the effect of total number of vehicles clearing the intersection per unit of effective green time on PCU value, PCU curves were drawn for a chosen vehicle category. Separate curves are drawn for different values of N keeping proportional composition of traffic stream constant. As mentioned earlier, the observed values of N at Nehru Place intersection were in the range of 0.8 to 1.4 vpsg. Therefore, simultaneous equations were solved for four distinct values of N taken in the observed range and keeping the proportional composition of traffic stream constant. Figure 4 shows the variation in PCU for bus with saturation flow rate, N. These curves have been drawn for fixed proportion of car and 2-wheeler as 20 and 30 per cent respectively, while the proportions of 3-wheeler and bus are varied from 5 to 45 per cent in a complementary manner. Similar curves for other two categories of vehicles are shown in Figures 5 and 6. It is observed that PCU for a vehicle type

at a specified composition of traffic stream, decreases with increase in the saturation flow rate. It is due to the fact that at higher value of saturation flow rate all vehicles are forced to move at much reduced but uniform speed, and therefore, PCU for a vehicle decreases as per equation (1). The effect of saturation flow rate on PCU, however, is not linear as may be seen from the vertical spacing between the curves at different proportion of the vehicle under consideration.

Variation in PCU with Approach Width

The behaviour of a vehicle clearing the intersection is very much affected by the space occupancy level (density) in the intersection area. If all other conditions of traffic stream remain unchanged, it will depend on the approach width alone. The larger the approach width, the lesser will be the density for a given value of saturation flow rate and composition of traffic stream. As a result, the longitudinal and lateral gaps between vehicles will increase at wider approaches causing more freedom to manoeuver. Vehicles will be able to accelerate at faster rate within the capabilities of their weight to power ratio. It will result in more speed differential between a car and another type of vehicle, and therefore, more PCU value for the latter. Figures 7 and 8 show the effect of approach width on PCU values for bus and 2-wheeler category of vehicles respectively. These curves have been generated for two approaches of 6.5m and 10.3m width keeping other traffic stream conditions constant. It may be observed that PCU for a vehicle type increases with the increase in approach width. This is due to the freedom of movement experienced by the individual vehicles at wider approaches as explained above.

Figure 7: **Effect of Approach Width on PCU for 2-Wheeler**

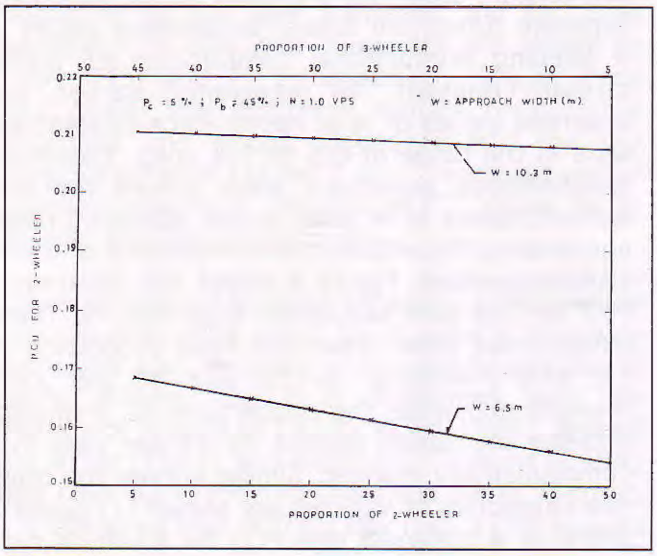
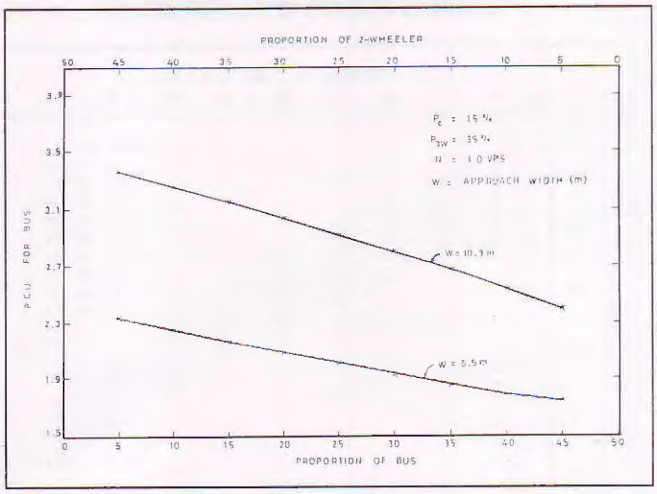


Figure 8: **Effect of Approach Width on PCU for Bus**



Saturation Flow as Related to Approach Width

Saturation flow values were calculated using the dynamic PCU values derived in this study. For that, PCU for each type of vehicle was determined for observed composition of traffic stream and then these values were used to convert all vehicles into equivalent number of cars. The results of saturation flow for different approach widths are given in Table 4.

Table 4: **Saturation Flow for Different Approach Widths**

Approach Width (metres)	Sat. Flow (pcuphg)	Number of Observations	Standard Error (%)
4.00	2250	46	8.7
6.25	3015	42	7.0
6.50	3086	45	10.4
10.30	4843	43	10.3
14.70	5211	42	6.6

Saturation flow values given in Table 4 were plotted against the approach width and a straight line relationship of the form given in equation 7 was found between these two parameters.

$$S = 1110 + 301 W \quad (7)$$

where S is the saturation flow in PCU per hour of green and W is the approach width in metres.

Conclusions

The increase in proportion of a vehicle type will certainly increase the level of interaction in the traffic stream, but it varies with manoeuverability and other operational characteristics of that type of vehicle. The simultaneous solution of equation system automatically accounts for mutual interaction of vehicles present in the traffic stream. Further, basic philosophy involved in the development of the concept of dynamic PCU had been that capacity estimation for an approach in a common unit must be the same irrespective of stream composition and other traffic flow parameters. This concept was validated form the results given in Table 4 where saturation flow values were computed using the observed proportion of traffic mix in each green phase of the intersection and converting all vehicles into a common unit using dynamic PCU values. Small variation shown in the form of standard error for each approach may be the result of grouping all the vehicle types into four categories only.

In this study the concept of dynamic PCU has been established. The effect of traffic composition and the actual level of interaction represented by saturation flow rate and approach width has been studied. Further, the behaviour of individual vehicle type changes with the level of service provided and therefore, dynamic PCUs need to related with Level of Service.

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